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Field Biogeochemical Measurements in Support of Remote Sensing Signatures and Characterization of Permafrost Terrain

Integrated Technologies for Delineating Permafrost and Ground-State Conditions

Robyn A. Barbato, John E. Anderson, Jarrod D. Edwards, Karen L. Foley, Charles M. Reynolds, and Thomas A. Douglas

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Abstract

This report highlights the acquisition of plant canopy spectral reflectance, leaf-level gas and fluorescence, and associated soil conditions at discrete locations along two transects located within the U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL), near Fairbanks, AK. Ecotones in interior Alaska have unique vegetative cover and heterogeneous terrains that are underlain by sporadic discontinuous permafrost. Permafrost thaw is expected to cause ecological consequences; and because vegetation and local soil microflora are tightly coupled, changes to this system offer a source of significant impacts on surface hydrology and soil strength.

The objective of this study was to investigate potential relationships between vegetative vigor and soil biochemistry in permafrost-affected areas for use in the development of standoff sensors for mapping the subsurface composition of permafrost terrains and to help in predicting how and where thawing permafrost will alter vegetation and soil ecology. Our results showed that redox chemistry is an important driver of ecosystem dynamics, and we identified relationships between fluorescence and reducing conditions at these transects. While it is well known that redoxymorphic conditions help drive plant composition in wetlands, it is less apparent how permafrost thaw influences this dynamic.

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Preface

This study was conducted for the Engineer Research and Development Center's Center-Directed Research Program under "Integrated Technologies for Delineating Permafrost and Ground-State Conditions." The technical monitor was Dr. Thomas A. Douglas, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL).

The work was performed by Dr. Robyn A. Barbato, Karen L. Foley, Dr. Charles M. Reynolds, and Dr. Thomas A. Douglas (Biogeochemical Sciences Branch, Dr. Justin Berman, Chief), ERDC-CRREL, and Dr. John E. Anderson and Jarrod D. Edwards (Geospatial Applications Branch, Tode Sims, Chief), ERDC Geospatial Research Laboratory (GRL). At the time of publication, Dr. Loren Wehmeyer was Acting Chief of the Research and Engineering Division of ERDC-CRREL. The Deputy Director was Dr. Lance Hansen, and the Director was Dr. Robert Davis. The Director of ERDC-GRL was Dr. Joseph Fontanella.

LTC John Tucker was Acting Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

ANOVA	Analysis of Variance
ASD	Analytical Spectral Devices
CR	Creamer's Field
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
ERDC	Engineer Research and Development Center
FL2	Farmer's Loop 2
FRI	Fluorescence Reflectance Index
GPS	Global Positioning System
GRL	U.S. Army Geospatial Research Laboratory
HARN	High Accuracy Reference Network
IRGA	Infrared Gas Analyzer
IRIS	Indicator of Reduction in Soils
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
ORP	Oxidative Reductive Potential
SE	Standard Error
TS	Tussock Sedge Site
TSS	Tussock Sedge and Spruce Site

1 Introduction

This report details relationships between soil pH and Eh and plant canopy spectral reflectance, leaf-level CO_2 emissions, and leaf-level fluorescence in discrete locations on two transects located within the U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL), Permafrost Research Station near Fairbanks, AK (Figure 1). Ecotones in interior Alaska have unique vegetative cover and terrains and are underlain by sporadic discontinuous permafrost. Their biogeochemistry is driven by strong seasonal changes in precipitation (Carey and Quinton 2005; Petrone et al. 2006; Bagard et al. 2011; Holmes et al. 2012; Douglas et al. 2013; Barker et al. 2014). In the next 80 years, mean annual temperatures in the interior of Alaska are expected to increase by 5°C (Chapman and Walsh 2007), likely initiating widespread permafrost degradation. The consequences of thawing permafrost are potentially significant, affecting overall ecological succession through alterations to specific processes, such as hydrology, vegetative cover, and soil activity (Racine and Walters 1994; Walker et al. 2006; Mackelprang et al. 2011; Wilhelm et al. 2011; Wolken et al. 2011).

Figure 1. An aerial image of the ERDC-CRREL Permafrost Research Sites north of Fairbanks, AK. The Creamer's Field locations are part of the Creamer's Field Migratory Refuge.

Jorgenson et al. (2001) have already documented changes in vegetative cover due to permafrost thaw in the region. The vegetative processes are tightly coupled to local soil microflora. Plant speciation influences microflora taxonomy; and soil microflora are integral in soil decomposition activity, which can affect nutrient bioavailability to plants (Zak and Kling 2006; Husson 2013; Kuzyakov and Xu 2013). In addition, soil microflora have the ability to respond quickly to changing soil moisture and biogeochemical conditions, thereby impacting nutrient availability in the rhizosphere. The coupled system is not only responsive to changing environmental conditions, but also can have significant impacts on surface hydrology and soil strength. In light of current climate change predictions, one concern is that areas that were once easily accessible may become inaccessible due to major changes in surface soil mechanical properties and hydrology.

The objective of our study was to investigate relationships between vegetative vigor and soil biochemistry in permafrost-affected areas. This will help to determine vegetation and soil characteristics that may have promise in the development of standoff remote sensing applications focused on identifying permafrost ground-state conditions.

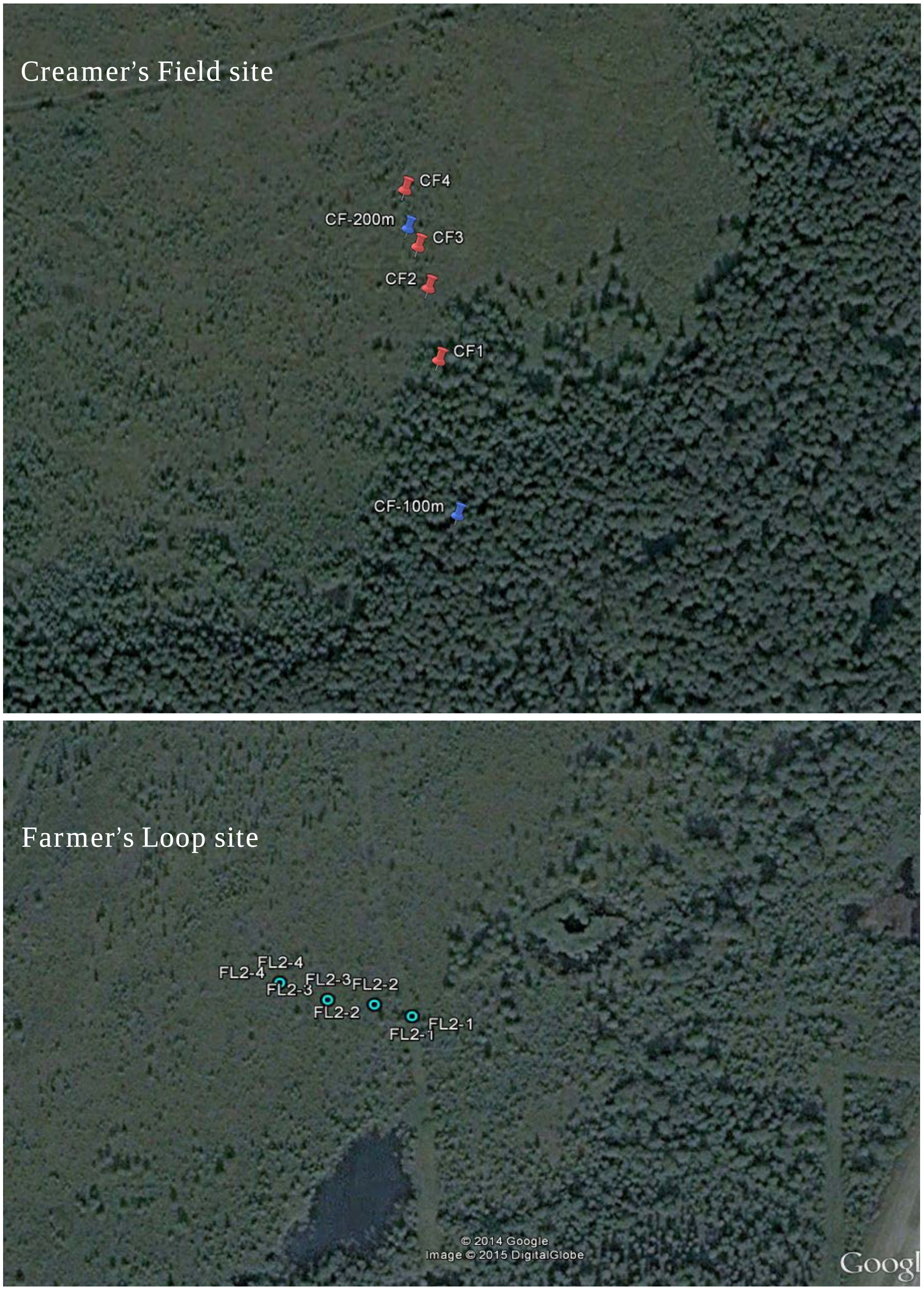
2 Study Location and Field Sites

Our study location was in the interior of Alaska, north of the Tanana River. Specific study sites were located at 64°52′09.39″ N, 147°44′20.31″ W (Creamer's Field [CR]), and 62°52′29.29″ N, 147°40′53.35″ W (Farmer's Loop 2 [FL2]) (Figure 1). Our objective was to collect field data across transects encompassing a variety of ecotones, from upland to wetland and bog.

Sample collection occurred during the peak local growing season in two summer campaigns (June to August, 2013 and 2014). We collected measurements along 100 m transects established at each site (Figure 3). A 1.5 m quadrat template was used to designate five sampling areas at 20 m intervals along each transect (Figure 2). Each quadrat was geographically located by GPS (global positioning system) survey using NAD83 (HARN) (North American Datum of 1983, High Accuracy Reference Network) in latitude and longitude and plotted in Google Earth .kml format. We corrected the GPS files by using the Online Positioning User Service (OPUS), NOAA (National Oceanic and Atmospheric Administration) National Ocean Service correction, in NAVD88 (North American Vertical Datum of 1988). Furthermore, we chose 1.5 m as a minimum mapping unit to represent the ground sample distance of future remote sensor data to be collected over the sampling research areas.

Figure 2. A typical sample-point layout using PVC to outline the quadrat.

Figure 3. Google Earth plot of surveyed GPS sampling points (*red pins*) along a 500 m transect (*blue pins* denote distance in meters along the transect). (In the figure, the “CF” designations refer to the Creamer’s Field sites.)



3 Materials and Methods

To investigate relationships between vegetative vigor and soil biochemistry in permafrost-affected areas, we collected

1. thaw probe measurements to characterize the extent of seasonal permafrost thaw;
2. soil redoxymorphic measurements to characterize the surface redox chemistry signatures that serve as controlling factors for the availability of exchangeable cations (i.e., Ca^{++} and Na^{+}), influencing vegetation composition and endemic microflora (Liebner et al. 2008; Wagner et al. 2009; Lee et al. 2013);
3. passive canopy reflectance spectrometry to provide effective control and classification selection for mapping plant communities using multi- and hyperspectral data sets; and
4. leaf-level stress measurements associated with pigment fluorescence to associate vegetative stress with certain spectral bands (and band ratios) in the hyperspectral data.

3.1 Site surveying and seasonal thaw measurements

At the end of summer (late September or early October) from 2011 to 2014, we determined the maximum seasonally thawed (active) layer depth at 1 m intervals along each transect. To probe the ground, we used a 1 cm diameter graduated metal rod that extended to as much as 2.5 m in length. To establish the distance between the ground surface and the ice-bonded base of the active layer, we pushed the rod downward vertically into the ground to the point of refusal (Shiklomanov et al. 2013). We used a high-resolution differential GPS to determine ground-surface elevations at 1 m intervals across each transect.

3.2 Soil redoxymorphic measurements

We determined redox potential by using an oxidative reductive potential (ORP) probe (Hanna Instruments, Woonsocket, RI) to obtain instant readings and Indicator of Reduction in Soils (IRIS) tubes (IRIStube.com) (Jenkinson and Franzmeier 2006) to obtain a long-term temporal measurement.

We used an ORP probe to collect field measurements of pH and Eh at the FL2 and CR transects in July 2014. We inserted a PVC pipe into the areas in between tussock sedges and collected pH and Eh measurements in triplicate per quadrat at each site (Figure 4). Prior to the soil freezing in early October of 2013, we installed IRIS tubes at two sites at the FL2 transect. One of these sites was composed of tussock sedge vegetation (designated the TS site) and the other harbored spruce trees, moss, and tussock sedge vegetation (designated the TSS site). We inserted a pipe into the ground to create a cylindrical hole and inserted the IRIS tubes, coated with $Fe(OH)_3$ (ferrihydrite), immediately afterward. The tubes were installed as nested quadruplicates in the middle of a tussock or in the low-lying area between tussocks (Figure 5). We collected one set of tubes 8.5 months later (early July 2014) and collected the second set approximately one year after installation (October 2014). Following removal, all tubes were rinsed with distilled water, air dried, and shipped to the ERDC-CRREL Laboratory in Hanover, NH. We used the absence of an iron oxide coating to estimate the soil redox potential during the time of exposure. Specifically, in the upper 30 cm of the IRIS tube, we visually recorded the percent loss of iron and manganese concretions over a volume of 104 cm^3 per Rabenhorst's (2008) method.

Figure 4. The sample area in between tussock sedges where pH and Eh were measured (white PVC pipe).

Figure 5. Nested IRIS tubes installed at the FL2 site in the tussock sedges and in the regions between the tussocks.

3.3 Canopy reflectance spectrometry

We acquired from the two sites (FL2 and CR) full-range (visible, near-infrared, and shortwave-infrared reflectance of vegetated canopies and ancillary targets by using an Analytical Spectral Devices (ASD) spectrometer in direct sunlight. We made measurements within the 1.5 m^2 sample template at a distance of 1 m at a field of view of 24° (0.83 m ground sample distance), and we collected and averaged ten measurements for each quadrat. Though we used a white National Institute of Standards and Technology (Halon) standard to calibrate the instrument, periodic cloud cover and overcast skies influenced the water bands in the shortwave infrared, rendering data after 1000 nm noisy. Therefore, high-quality data collected during the 2014 sampling period were sparse. We truncated the resulting data files to represent only the visible to near-infrared plant response to accommodate for this loss; however, the near-infrared region is critical to indices calculations related to leaf-level physiological metrics, as described in Section 4.3 below.

Leaf-level infrared gas analyzer (IRGA) and pulse-modulated fluorescence measurements acquired on vegetation within the sample plots provided base physiology, including a *net* photosynthesis, conductance, intracellular CO_2 (C_i), and Fluorescence (ΔF). We collected measurements on individual leaves of plants by using the LI-6400 IRGA leaf chamber (LI-COR Inc., NE) (Figure 6).

Figure 6. Canopy spectral reflectance collection (*left*) and leaf-level IRGA (*right*) at FL2 and CR sites.

4 Results and Discussion

4.1 Site surveying and seasonal thaw measurements

Figures 7 and 8 include seasonally thawed measurements collected in the transects in 2014. Patterns were similar in 2013, but the measurements were collected more frequently in 2014. Results show the variability in frost probe depth along both transects. Generally, the frost probe depths increased from June 2014 to August 2014 at both the FL2 and CR transects. At both sites, there were minimal increases in frost probe depth from August 2014 to October 2014.

Figure 7. Results from thaw probe measurements of the seasonally thawed "active" layer along the FL2 transect.

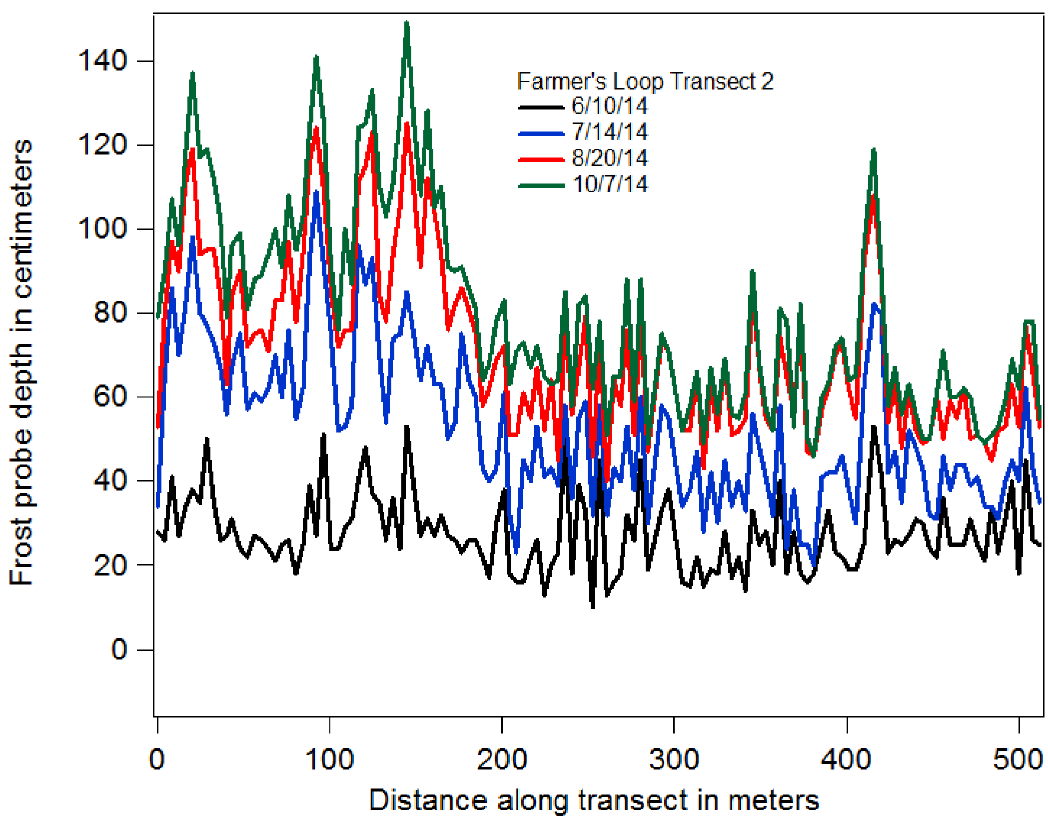
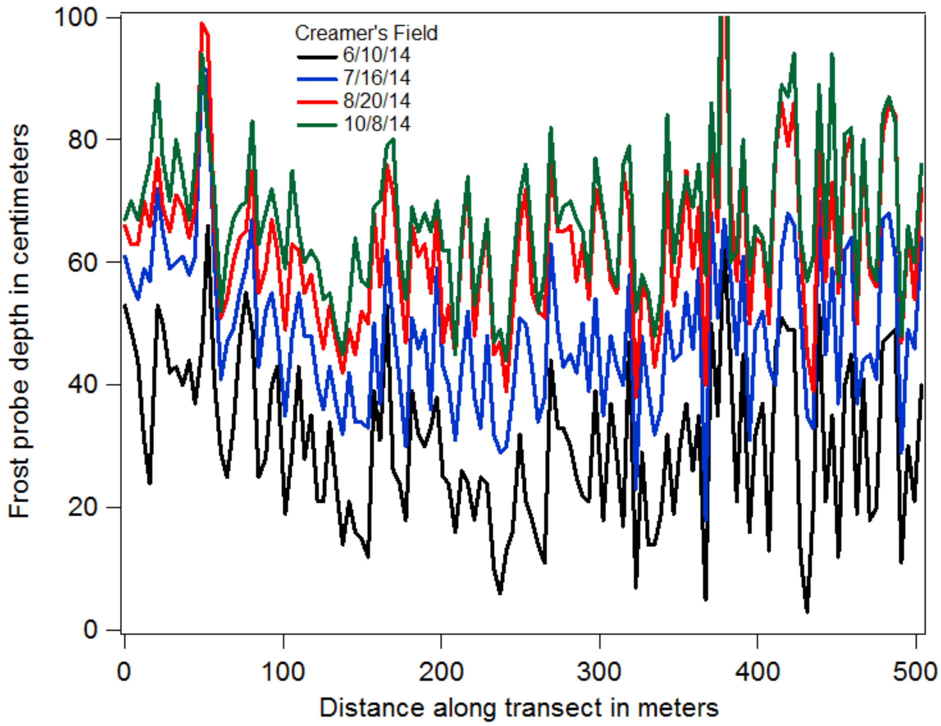


Figure 8. Results from thaw probe measurements of the seasonally thawed "active layer" along the CR transect.



4.2 Redox—ORP

Environmental properties, such as pH and ORP (Eh), influence ecosystem dynamics. Anoxic conditions in the soil may be driven by processes in the seasonally thawed soil layer ("active layer") that overlies the permafrost. We hypothesized that these differences in the active-layer redox state would be reflected in differences in overlying vegetation. It has been observed in wetlands not influenced by permafrost that plant stress and plant zonation were controlled by factors such as periodic flooding and seasonal inundation (Heinselman 1970; Moore and Bellamy 1974). These factors drive soil redox conditions, in particular anaerobic processes.

Typically, soil Eh fluctuates between −300 and 900 mV; and soils below 300 mV are characterized as waterlogged soils (Husson 2013). Further, reducing conditions have been found to be quite limiting for plants (Husson 2013). At the Alaskan field sites, soil redox ranged from 4.5 to 312 mV between tussocks (Figure 9, *right*). Eh at the CR transect was significantly higher ($P < 0.0001$) than at the FL2 transect, suggesting that the soils between tussocks across the FL2 transect were more reducing (Figure 9, *right*). Berkowitz et al. (forthcoming) also observed instances of reducing conditions at both the FL2 and CR transects though did not find signif-

icant trends between the two transects. We observed that pH did not change dramatically across the FL2 transect but did vary across the CR transect (Figure 9, *left*). Reduction potential is often influenced by pH, such that Eh increases when there are more hydrogen ions in the reaction. Our results show a negative correlation between Eh and pH (Figure 10), which is common in all soils (Bohrerova et al. 2004; Husson 2013).

We could infer from the redox measurements whether a site was predominantly aerobic or anaerobic. This is especially important in Alaskan wetland systems where soil hydrology effects plant composition and vigor. Because reducing conditions also select for particular populations of microorganisms (Madigan et al. 2002), we could infer the presence of specific organisms based on the redox values measured. For instance, the conversion of nitrate to nitrogen gas and nitrous oxide likely occurred above an Eh of 200 mV, suggesting that it was energetically favorable for denitrifying bacteria to conduct these reactions (Figure 9, *right*). Likewise, manganese reduction likely occurred between 125 and 200 mV; and iron reduction was energetically favorable below 125 mV (Figure 9, *right*). Therefore, iron-reducing bacteria were expected to be more abundant at FL2 whereas nitrate reducers would be more abundant at CR (Figure 9, *right*). Additionally, fungi are more abundant under moderately reducing conditions (Seo and DeLaune 2010) and could potentially have been more abundant in soils from the FL2 transect. However, those microorganisms would need to be detected at the respective locations to confirm the inferences. The presence of those microorganisms is fundamental in our attempt to couple plant stress to soil dynamics and to provide understanding of *mycorrhizal* symbiotic associations influencing plant stress (e.g., nutrients and toxicants) in permafrost regimes (Entry et al. 2002).

Figure 9. Measurements of pH (*left*) and Eh (*right*) at FL2 (*red circles*) and CR (*yellow circles*) transects. Here, n=3, and error bars indicate SE (standard error).

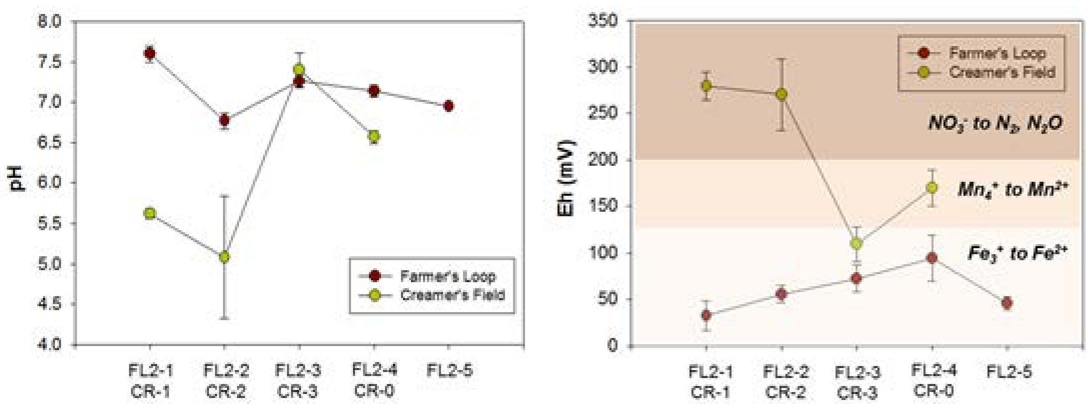
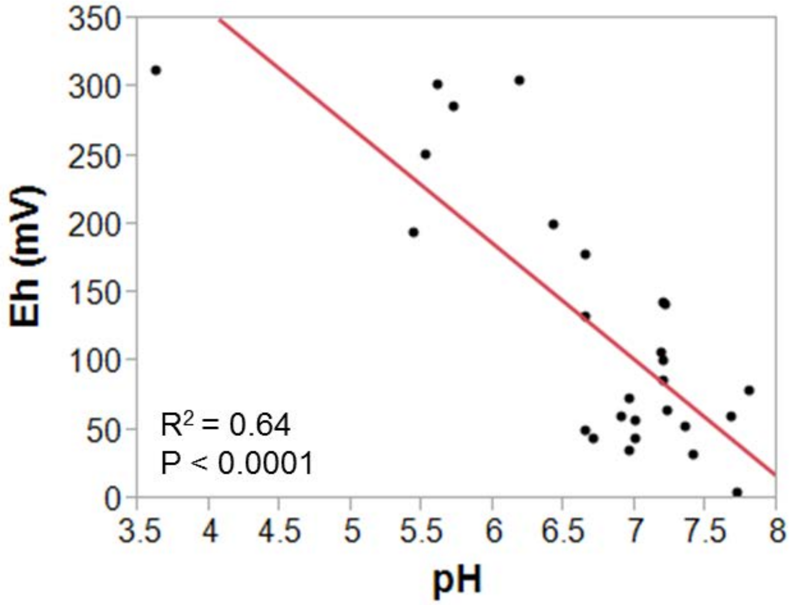


Figure 10. Negative correlation between pH and Eh measurements at FL2 and CR transects.



4.3 Redox—IRIS tubes

OPR readings provide instantaneous measurements of redox potential; however, there are both spatial and temporal variations associated with those measurements (Husson 2013). Therefore, we installed IRIS tubes at two locations (tussock sedge site [TS] and tussock sedge and spruce site [TSS]) in the FL2 transect to reveal temporal evidence of reduction. Figure 11 shows the varying degree of iron reduction observed at the FL2 transect, which ranged from no reduction to complete reduction. To investigate iron reduction through winter freezing and subsequent summer thawing of the seasonally thawed surface soil layer, we installed the IRIS tubes before the ground froze.

After eight months of field incubation, the TS site exhibited a higher incidence of iron reduction when compared to the TSS site (Table 1). The TSS site was a spruce-dominated ecotone, suggesting reduced thaw and, therefore, a higher incidence of non-reducing conditions. Soil water content, as driven by precipitation patterns and influenced by permafrost degradation, could also influence the amount of reduction occurring at a particular location. For example, locations between tussocks were more reducing at both the TS and TSS sites (Table 1). We expected this result because the low-lying regions between tussocks were typically waterlogged.

Figure 11. Example IRIS tubes with varying degrees of iron reduction.

Table 1. Percent reduction (mean ± SE) of ferrihydrite coating on IRIS tubes after 7.5 months of field incubation at the FL2 transect. Here, n=4 unless tubes were not collected due to being frozen in permafrost.

Site	n	Location	Reduction (%)
TS	4	Tussock	32 ± 0.2
	2	Between Tussock	41 ± 3.5
TSS	4	Tussock	2 ± 1.1
	3	Between Tussock	9 ± 3.0

Following an additional year of incubation, we again collected the IRIS tubes for analysis though we did not identify tussock and between tussock locations. The TS site exhibited 85 ± 10.3% in iron reduction; and the TSS site exhibited 20 ± 7.4% in iron reduction, indicating higher reducing conditions at the TS site. These values were higher than those from the 7.5-month incubation, suggesting an increase in reducing conditions as the permafrost continued to thaw seasonally from July to October (Figure 7). Table 2 includes a summary of the seasonally thawed active-layer depth measurements from the TS and TSS sites. At the TS site, seasonal thaw was significantly greater in the areas through the tussocks than between the tussocks. However, we observed no significant difference in seasonal thaw between the TSS sites and the between-tussocks TS sites (Table 2).

Table 2. A summary of seasonally thawed (active layer) measurements from the FL2 transect.

	Birch Forest	TS—Through Tussocks	TS—Between Tussocks	TSS
Number	42	23	29	23
Mean	107.3	77.2	58.4	60
Standard Deviation	18	7.2	6.2	8.3
ANOVA*	A	B	C	C

*Results from an analysis of variance (ANOVA). Unique letters correspond to significantly different ($\alpha < 0.05$) populations.

4.4 Spectral reflectance and IRGA (LI-COR) leaf-level data

During the 2013 and 2014 sampling periods, we collected and recorded a total of 14 plant species from both field transects. These plants represented the dominant canopy species measured using reflectance spectrometry. From the standpoint of diversity, FL2 had the highest diversity (H' = 9.003) as determined by the Shannon Index ($H' = -\Sigma\, p, ln\, [p_1]$). The plant diversity across the CR transect was lower at H'= 7.708. Diversity as a measure in wetlands can be linked to periods of flooding and productivity (Mitsch and Gosselink 1986). We would expect to find more organic matter in areas harboring higher plant diversity, giving rise to more species. However, peatlands are typically low in diversity when compared to other wetlands, for example, tidal and non-tidal systems. The production of biomass is hypothesized to be affected by permafrost thaw, which should in turn affect plant canopy composition. As more moisture is introduced into the soil, peat accumulates readily due to the lack of oxygen-driven decomposition.

Leaf-level stress studies (funded by the Army Basic Research Program) have shown that various spectral indices relate strongly to select biogeochemical attributes (including redoxymorphic-influenced stress) and to leaf-level optical measurements (Naumann et al. 2008, 2009; Anderson and Perry 1996). Coupled with the synoptic view of the landscape and these relationships, terrain state affected by permafrost might be characterized effectively from narrowband multi- and hyperspectral imagery data.

In collecting infrared gas analyzer (IRGA), we hypothesized algorithms, from the near–infrared region (e.g., Fluorescence Reflectance Index; [FRI]) representing a fraction of the fluorescence emission, could be linked to specific environmental parameters (e.g., hydrology) to quantify variation in permafrost terrain state. This is because the seasonal and long-term response of permafrost to changing thermal conditions is inti-

mately controlled by hydrology at the local to regional scale (Tarnocai and Campbell 2002; Davidson and Janssens 2006; Allison and Treseder 2011; Johnson et al. 2011; Sierra et al. 2011; Douglas et al. 2013, 2014). Further, fen, bog, and marsh systems, often linked hydrologically to lakes and ponds, play major roles in nutrient cycling between aquatic and terrestrial permafrost ecosystems (Fan et al. 2013; Rober et al. 2014).

Canopy spectra reflectance was used in correlations with IRGA data to construct the FRI: $FL_{ref} = R761\ nm\ /\ R757\ nm$. We also recorded CO_2 and water vapor at the field sites by using the IRGA LI-6400. We used pulse-modulated fluorescence (blue and red wavelengths) to measure day-adapted (Fm') fluorescence to compute ΔF as $(Fm' - Fs')\ /\ Fm'$ (where Fm is the day-adapted fluorescence and Fs is the steady-state). These terms describe the energy flow profile of the plant photosystem where excess energy is expressed as a function of natural or anthropogenic stress. The formula yielded results shown to correlate with spectral reflectance as a function of the “fill-in” or contribution of fluorescence to the reflectance signal (approximately 3%–4%) between 680 and 800 nm (Figure 12). This stress marker is significant in synoptic remote sensor data and has been observed in narrowband imaging (e.g., field radiometry and hyperspectral imagery) as reported by Zarco-Tejada et al. (2003). We also correlated *net* photosynthesis and *Ci* (internal CO_2) as a check on the LI-COR measurements. Correlations were positive (about $R^2 = 0.50$) for all sites in 2013 but were inconclusive in 2014 due to instrument problems and weather. The ΔF and FL_{ref} were correlated for both years despite weather issues with the spectral collection in 2014. This in part addresses our hypothesis tying field (optical) stress measurements of plant photosystems to spectral reflectance. The results are consistent with previous findings by Naumann et al. (2008, 2009) linking physiological measurements (e.g., IRGA data) to spectral reflectance indices. Once image spectrometry is acquired over the research sites, we anticipate using these data to evaluate field-level to airborne and space-level spectral relationships. Figure 13 presents correlations between ΔF and FL_{ref} for the 2013 collections.

Figure 12. ASD canopy reflectance for FL2 transect samples. Shading indicates the region of the fluorescence "fill-in" of the reflectance continuum between 680 and 800 nm.

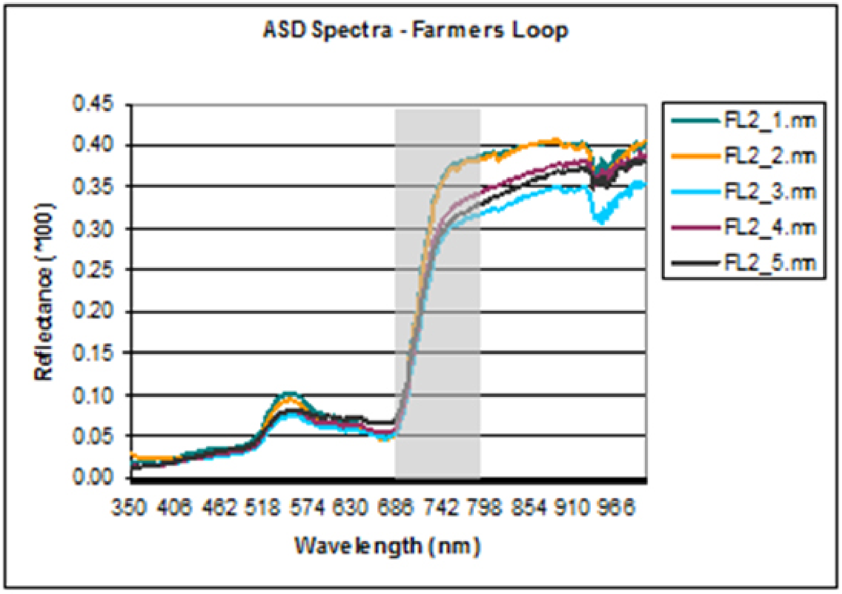
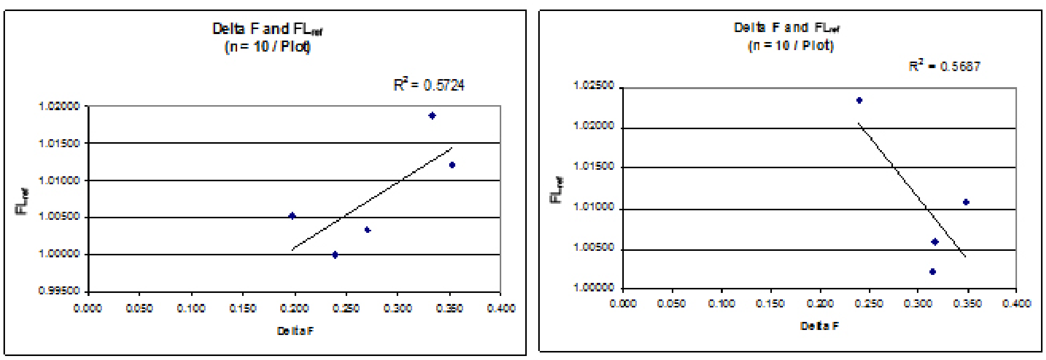


Figure 13. Correlations between LI-COR leaf-level and canopy-level fluorescence based on the ASD Fluorescence Reflectance Index.



Given the poor set of data representing the field spectral collection and attempted hyperspectral imaging during the 2014 sampling event, we were unable to apply remote sensing indices to a highly controlled spectral image data set. Although correlations between canopy reflectance and leaf-level fluorescence using the FRI were surprisingly good, the record wet summer weather hampered our attempts to acquire 2014 model data and imagery to test the critical FRI index. It is interesting to note that reflectance and LI-COR IRGA did show good correlations and trends for each site ($R^2 > 0.50$) as measured at FL2 and CR across the ecotone from "upland" into the bog system. The CR site showed decreasing ΔF across the established gradient. The site also had the most complex and undulating

terrain, dominated by herbs and small shrubs of low plant diversity. Image data using the ratio FL_{ref} *R761 / R757* may help demonstrate the extent of this trend. Figure 13 provides a graphical presentation of fluorescence trends in the plant canopies at the sites. As 2013 was a more normal-to-dry year and 2014 was a record wet year, these graphs suggest that IRGA can document plant stress by using leaf-level metrics. For 2013 at the CR transect, we observed less stress toward the wetter bog side of the ecotone (quadrats CR_2 to 0). In 2014, this trend was reversed with more stress observed for sampled plants in the inundated bog. The data for the FL2 transect show more stress characterized in plants in the bog (quadrats FLT2_2 to 5) during the drier year. Finally, we explored the chance that permafrost depth may correlate with FL_{ref}, but we did not find conclusive evidence of a relationship between these variables in either collection.

This was surprising as peat has a high moisture capacity. This trend continued for wet year measurements, with the exception of quadrat 5. Although these data represent only two sampling intervals during the local growing season, they support well-grounded research in vegetation remote sensing and the use of such data in classification to understand terrain feature condition.

Figure 14. Correlation between FL_{ref} and permafrost depth. We observed no other correlations for these variables in 2013 and 2014.

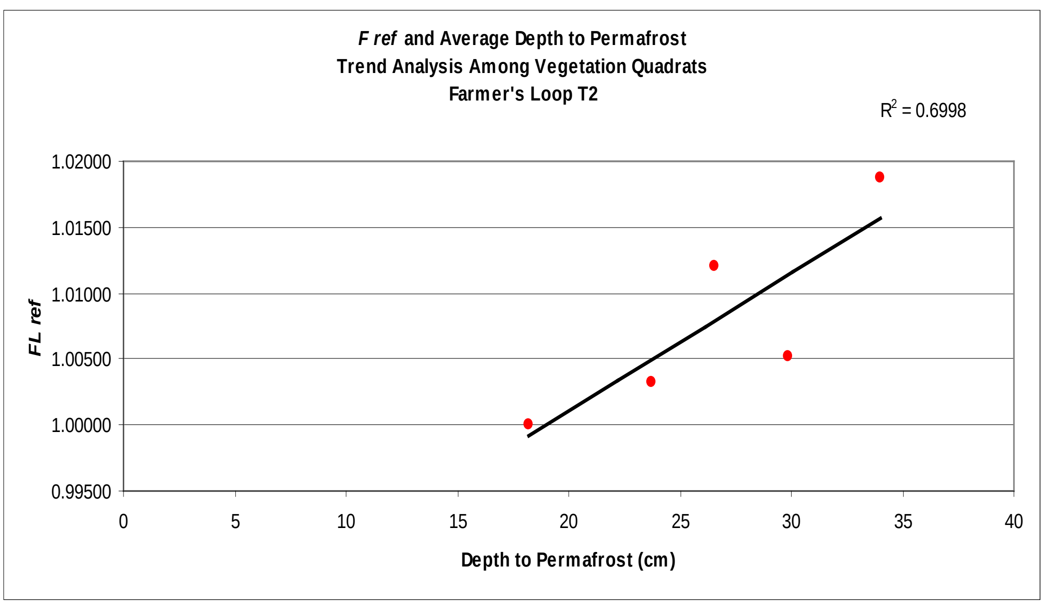
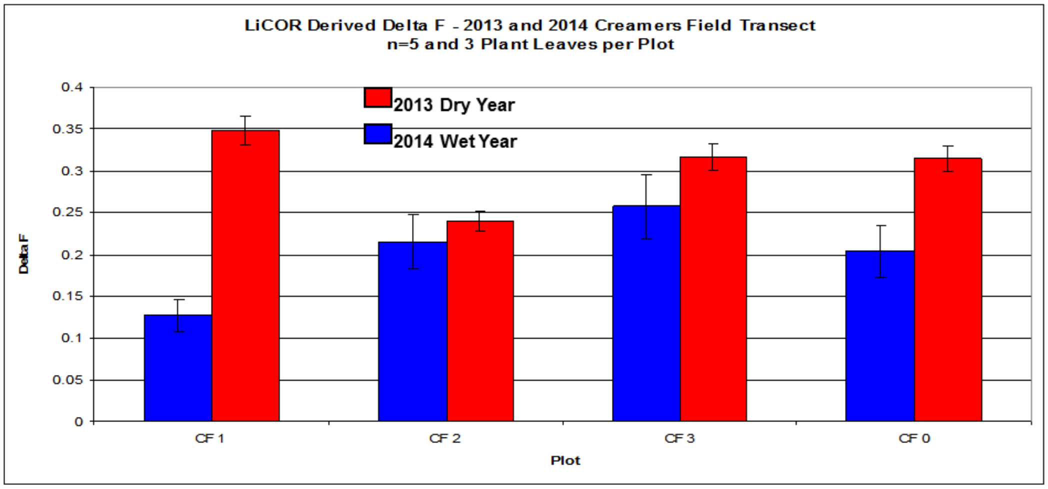
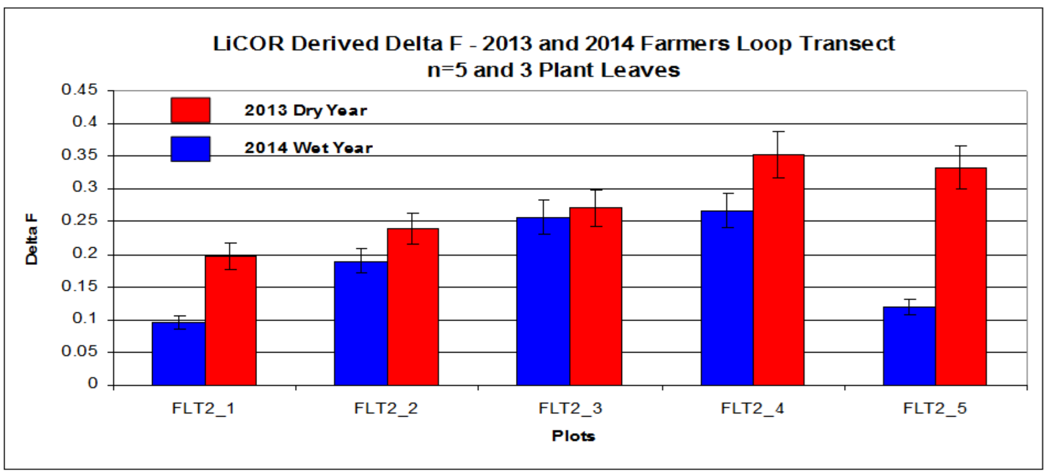


Figure 15. *Top*, LI-COR fluorescence trends for CR showing dry- versus wet-year influences with stress indicated by an elevated fluorescence value: *ΔF*—the difference between the light-adapted steady-state fluorescence and maxima. *Bottom*, LI-COR fluorescence trends for FL2 showing dry- versus wet-year influences with stress indicated by elevated fluorescence (*ΔF*)





5 Conclusions

Redox chemistry is an important driver of ecosystem dynamics, both on the microbial and plant trophic levels. We used two techniques, ORP and IRIS tubes, to describe soil redox potential along two transects in interior Alaska. Our results showed that Eh, as measured using the ORP, was more reducing at the FL2 transect, suggesting a higher incidence of iron reduction at this site. At the FL2 transect, we identified a weak correlation between leaf-level fluorescence (ΔF) and Eh (Figure 16). When investigating this relationship further at both transects, ΔF and Eh showed a significant positive correlation (Table 3). This relationship should be more completely explored given the influence permafrost thaw may have in these systems. We found a correlation between FL_{ref} and permafrost depth at the FL2 transect, but not at the CR transect, and found no correlations between FL_{ref} and permafrost depth in 2014. While Eh as measured by ORP is informative, more frequent sampling will be necessary to understand the temporal and spatial variation associated with redox chemistry in these soils.

Figure 16. Correlation between Eh and ΔF.

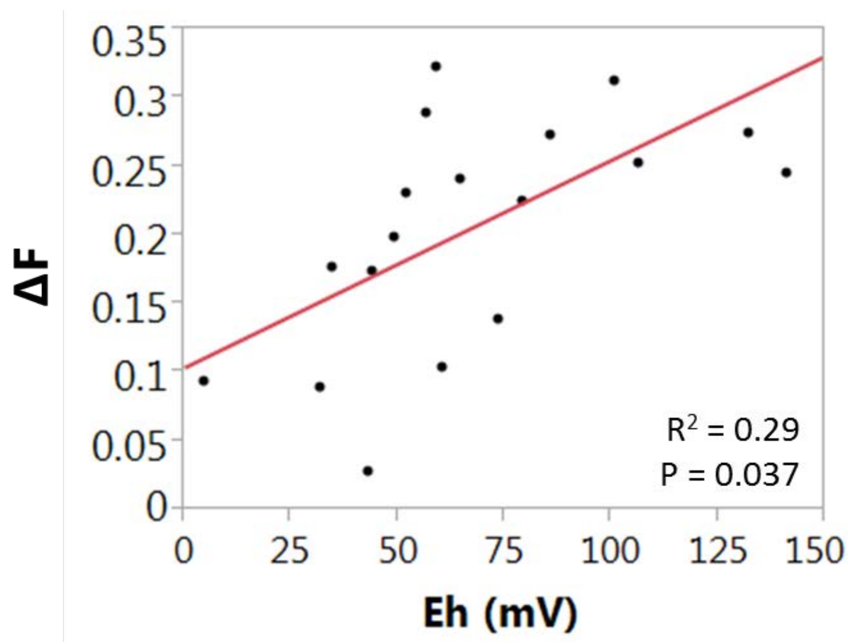


Table 3. Spearman's ρ Correlations from the FL2 and CR transects.

Variable 1	Variable 2	Spearman's ρ
Eh	pH	−0.0215
Eh	Depth to Permafrost	0.3915
Eh	ΔF	0.6393*
pH	Depth to Permafrost	−0.6643*
pH	ΔF	−0.2650
Depth to Permafrost	ΔF	0.3527

* $\alpha < 0.05$

Within the FL2 transect, we observed increases in iron reduction on the IRIS tubes over the course of the summer season, providing evidence of increased iron reduction as the permafrost thawed. A recent study from the continuous permafrost zone in northern Alaska used trace metals (including iron) to track the downward migration of the seasonally thawed layer (Barker et al. 2014). Based on the results from that study and from ours, we suggest that future research efforts should focus on redox chemistry and the relationship to vegetative response in Alaskan peatlands. While it is well known that redoxymorphic conditions help drive plant composition in wetlands, it is less apparent how permafrost thaw influences this dynamic.

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14. ABSTRACT

This report highlights the acquisition of plant canopy spectral reflectance, leaf-level gas and fluorescence, and associated soil conditions at discrete locations along two transects located within the U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL), near Fairbanks, AK. Ecotones in interior Alaska have unique vegetative cover and heterogeneous terrains that are underlain by sporadic discontinuous permafrost. Permafrost thaw is expected to cause ecological consequences; and because vegetation and local soil microflora are tightly coupled, changes to this system offer a source of significant impacts on surface hydrology and soil strength.

The objective of this study was to investigate potential relationships between vegetative vigor and soil biochemistry in permafrost-affected areas for use in the development of standoff sensors for mapping the subsurface composition of permafrost terrains and to help in predicting how and where thawing permafrost will alter vegetation and soil ecology. Our results showed that redox chemistry is an important driver of ecosystem dynamics, and we identified relationships between fluorescence and reducing conditions at these transects. While it is well known that redoxymorphic conditions help drive plant composition in wetlands, it is less apparent how permafrost thaw influences this dynamic.

15. SUBJECT TERMS

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